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OLEDs: Light-emitting thin film thermistors revealing advanced self-heating effects

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ABSTRACT

Large area OLEDs show pronounced Joule self-heating at high brightness. This heating induces brightness inhomogeneities, drastically increasing beyond a certain current level. We discuss this behavior considering 'S'-shaped negative differential resistance upon self-heating, even allowing for 'switched-back' regions where the luminance finally decreases (Fischer et al., Adv. Funct. Mater. 2014, **24**, 3367). By using a multi-physics simulation the device characteristics can be modeled, resulting in a comprehensive understanding of the problem. Here, we present results for an OLED lighting panel considered for commercial application. It turns out that the strong electrothermal feedback in OLEDs prevents high luminance combined with a high degree of homogeneity unless new optimization strategies are considered.

Keywords: Organic light-emitting diode OLED, Joule self-heating, Brightness inhomogeneity, Negative differential resistance, Electrothermal feedback, Lighting panel, Organic semiconductor, Large area

1. INTRODUCTION

For lighting applications, OLEDs operate at much higher brightness than for displays,[1] causing substantial self-heating accompanied by brightness inhomogeneities. Although the relevance of electrothermal interplay has been recognized, a fundamental understanding is still missing.[2–5] For example, an explanation why regions of highest temperatures shift to the device borders albeit the heat conduction is worst at the center of the substrate does not exist. Furthermore, large area OLED panels can show a saturation of brightness around their mid position at elevated self-heating.[6]

In general, the efficacy of the panels has to be increased to a level at which an application relevant luminance is already reached before self-heating occurs. Although white OLEDs are highly efficient nowadays,[7] larger lighting panels (width $\sim 10\,\mathrm{cm}$) do not reach much more than $3000\,\mathrm{cd/m^2}$ before first inhomogeneities arise.[8] At this brightness, the cost efficiency, e.g. given in lm/$, is still too low to justify a mass production. For example, OLED lighting still lies below 10 lm/$ while conventional light sources such as LEDs, energy saving lamps, or tube lights are clearly above 100 lm/$.

Further improvement in efficacy of white OLEDs can be expected by new light outcoupling techniques[9] and by higher efficiencies of the emitter molecule, e.g. by using blue emitters showing thermally activated delayed

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fluorescence,[10] but an overall enhancement of more than 50% would already be huge. Hence, a stable and homogeneous device operation at higher current densities is mandatory in order to achieve higher brightness. In this case, the light output increases while the manufacturing costs remain constant, improving the cost efficiency and minimizing the hurdles for future market entry. However, elevated Joule self-heating is accompanied by an unpleasant inhomogeneous appearance of the lighting panels. The trivial solution would be to prevent heating by cooling solutions. This could be either done by using a metal substrate or by realizing contact to a cooling body/liquid.[11,12] Such approaches, however, typically prevent lighting panels to be produced on transparent or highly flexible substrates. After a certain time, the cooling body also heats up. An efficient heat transfer to the environment has to be guaranteed, so that the use of OLEDs for new designs and new fields of application is reduced, which is one of the main advantages of OLED technique.

The approach we favor is using an improved understanding of the electrothermal feedback in OLEDs in order to generate future concepts that incorporate self-heating. Therefore, we discuss in this article our latest results on a large area lighting panel (7.5 cm × 15 cm) in more detail and explain the underlying physics.

Recently, we have shown that the temperature-activated transport in C_{60} devices favors thermal runaway as a result of negative differential resistance (NDR) of 'S'-shape type.[13] The effect can be fully explained by electrothermal effects arising from the positive feedback loop between the temperature dependent conductivity and the power dissipation. Such a behavior is well-known for thermistor devices with a negative temperature coefficient (NTC),[14,15] but has not been shown for organic semiconductor devices before.

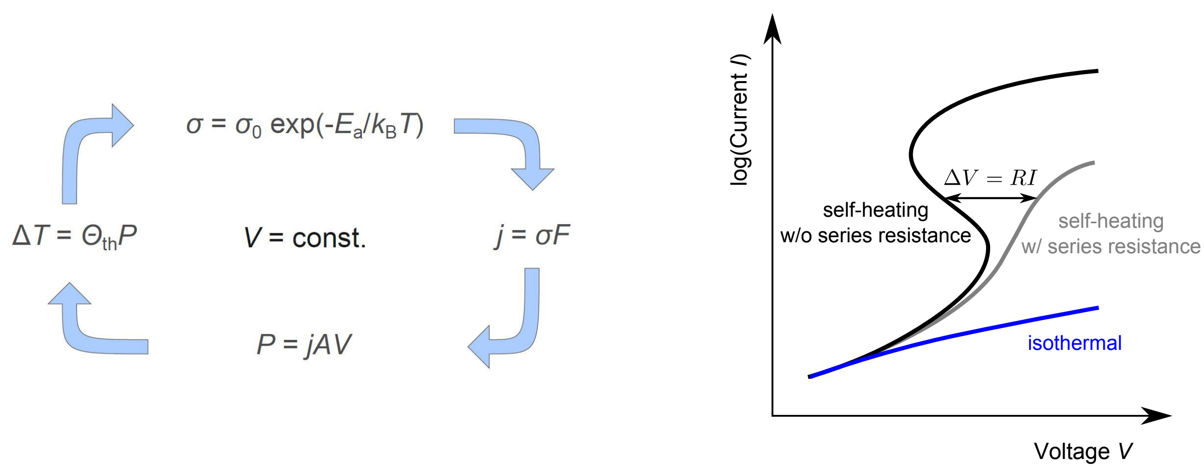


Figure 1. Left: Positive feedback loop of the electrothermal interaction as present in an OLED. The current density j results in a power dissipation P, increasing in turn the temperature T via a finite thermal resistance Θ_{th}. The higher temperature leads to an increase of the Arrhenius law temperature-activated conductivity, resulting in a growing current. The behavior is known from thermistor devices with negative temperature coefficient (NTC).[14] Right: Schematic IV curve (black), showing the S-shaped IV curve of a single thermistor. When a resistor R is in series to the thermistor (grey), it is possible that the NDR is not observed. However, the thermistor itself still operates in the NDR regime upon a certain current I. For comparison, an isothermal IV curve (blue) corresponding to e.g. a power law is added.

Figure 1 shows the positive feedback loop in detail. At a constant voltage, the current flow j is related to a power dissipation P by Joule self-heating. The temperature T of the substrate increases proportional to the thermal resistance Θ_{th} which in turn enhances the conductivity. A feedback originates that can be treated analytically for an Arrhenius-like conductivity-temperature law having an activation energy E_{a}.[13] For low voltages, a stable solution exists so that the feedback loop converges. However, with rising voltages, the electrothermal feedback becomes so strong that the problem diverges (thermal runaway) and only saturates at an upper branch given by the limited conductivity of the $\sigma(T)$ relation for $T \to \infty$. The switching phenomena are typically accompanied by thermal breakdown of the test structure, unless a protecting series resistance is used, able to limit the currents at the upper branch, but still preserving the switching. Turnover points where the switching occurs are directly related to the voltage range of the unstable NDR region of the thermistor.[13] One can stabilize this NDR regime by using either a sufficiently high series resistance or by measuring in constant current mode, so that for each current a unique solution for the voltage is obtained (cf. Fig. 5 b)). Here, 4-wire crossbar measurements have allowed to demonstrate S-NDR due to self-heating at constant current, e.g. as published for a red, green, and blue OLED.[6]

2. RESULTS

2.1 Experimental characterization

To demonstrate the effect of electrothermal feedback in OLED lighting panels, we use a Tabola lighting panel produced by Fraunhofer FEP/COMEDD (Dresden, Germany). The device stack consists of a 3-unit-stacked architecture based on a fluorescent blue, phosphorescent green, and phosphorescent orange unit, realizing warm white light emission. Figure 2 shows the spatial distribution of temperature and luminance at a current of 1 A ($\sim 10\,\mathrm{mA/cm^2}$), respectively. For a device with a constant current density, it is expected to have the highest temperatures in the center of the tile where the heat conduction into the environment is worst. However, one finds the temperature maxima at the edges, already indicating a strong inhomogeneity of the current flow. This observation is further confirmed by video photometry. At the highest currents, the brightest areas are found to be close to the edges where the highly conductive support electrode enhances the current supply by the transparent electrode. It should be noted here that even without electrothermal feedback such a behavior can occur due to the sheet resistance of the electrodes causing a lateral potential drop. Nevertheless, electrothermal feedback is able to significantly enhance these inhomogeneities.

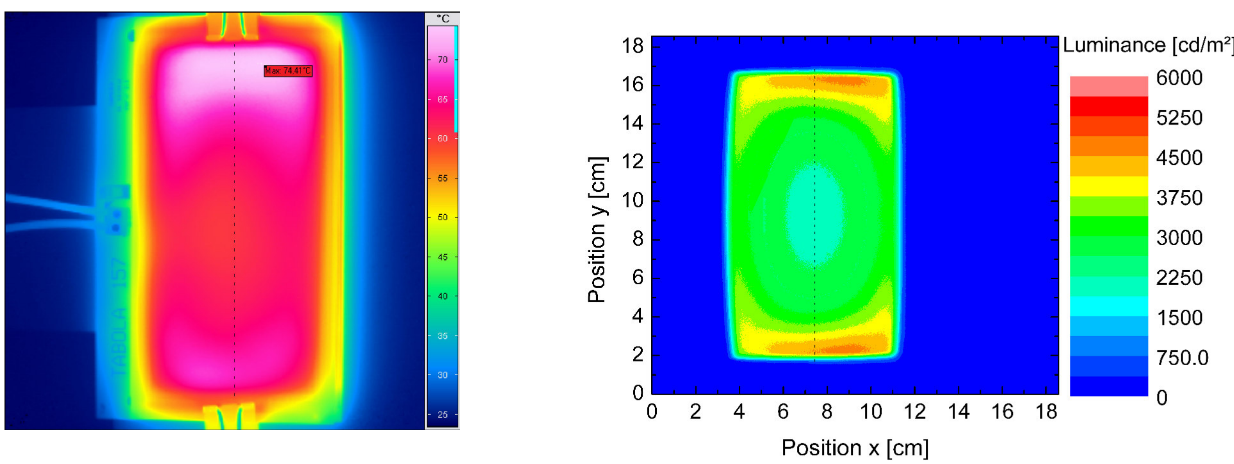


Figure 2. Thermal imaging (left) and video photometry (right) of a Tabola lighting panel at a constant current of 1 A. The dashed line shows where the profiles of Fig. 3 are extracted. Reproduced with permission.[6] Copyright (c) 2014 Wiley-VCH.

This becomes more clear in Fig. 3 where in a) the profiles of the luminance and in b) the temperature are shown along the larger symmetry axis. The lighting panels exhibits uniform light emission up to $1000\,\mathrm{cd/m^2}$ but the uniformity drastically decreases when currents above 500 mA are exceeded. The emission at the edges continues to increase with the applied current while the center region saturates, i.e. it is not possible to exceed a luminance of $3000\,\mathrm{cd/m^2}$ there at any current. Such a behavior cannot solely be explained by the sheet resistance of the electrodes. Especially, the transition from an homogeneous emission to a strong inhomogeneity is very sharp and happens within a narrow range of total currents. Hence, it remains impossible to simply apply higher currents to large area OLEDs in order to achieve higher light output even though the materials would withstand higher temperatures. The lighting panel investigated here revealed stable operation at 1 A and peak temperatures around 75 °C, having almost no degradation during the measurement. The temperature distribution reveals that degradation does not cause the saturation of the luminance at the central position. The highest temperatures

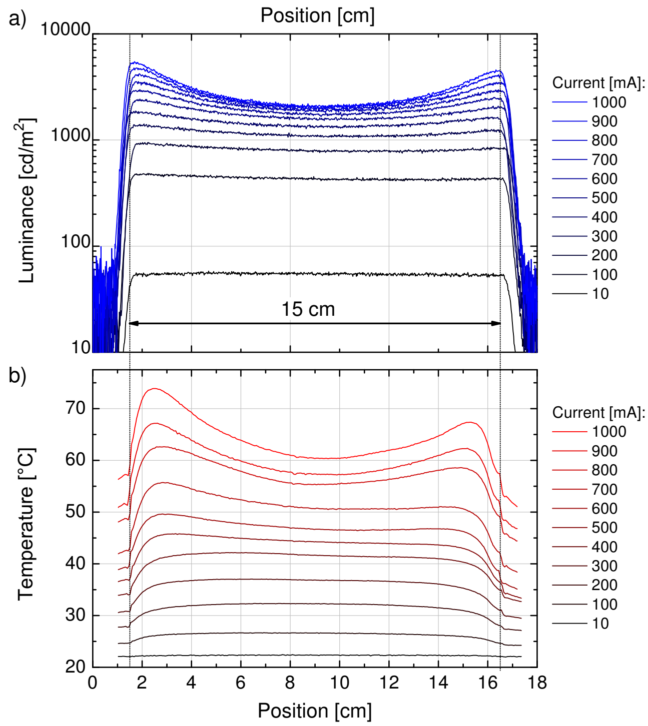


Figure 3. Profiles of the a) luminance and b) the temperature along the larger symmetry axis of the Tabola lighting panel as indicated by the dashed line in Fig. 2. Reproduced with permission.[6] Copyright (c) 2014 Wiley-VCH.

occur rather at the edges of the active area and not in the center of the lighting panel. Only at lowest currents, one can see that the central region shows maximum temperature, as expected for a homogeneous current density.

2.2 Simulation

A qualitative understanding of the effects taking place can be achieved by using a multi-physics network simulation. For that purpose, we use an electrical network simulation program (LTspice IV, Linear Technology USA). Two independent networks for the electrical as well as for the thermal properties are generated. They are coupled by an array of thermistor devices representing each lateral part of OLED. Every thermistor follows a power law IV characteristic, e.g. fitted from experimental data at isothermal operation, modified by an Arrhenius-like conductivity-temperature law. All thermistors are connected by a quadratic network of resistors, representing either the cathode or anode with values corresponding to the sheet resistance of the electrodes. More details on the simulation are described in Ref. 6.

The simulation result for a large area lighting panel is given in Fig. 4. Up to 500 mA, the homogeneity of the lighting panel is preserved, but for larger currents, the light emission concentrates at the corners of the active area. By comparing the central positions of each picture, one can clearly see that the luminance does not further rise with the applied current, as also observed in experiment. The effect can be investigated in more detail when the local differential resistance

$$R_{\mathrm{ij}} = \frac{\mathrm{d}\,V_{\mathrm{ij}}}{\mathrm{d}I_{\mathrm{ij}}} = \frac{\mathrm{d}\,V_{\mathrm{ij}}}{\mathrm{d}I}\left(\frac{\mathrm{d}I_{\mathrm{ij}}}{\mathrm{d}I}\right)^{-1} \tag{1}$$

is evaluated at each point (i,j) of the thermistor network. Figure 5 b) presents a table of relevant scenarios. Likewise to Eq. (1), the local differential resistance is defined with respect to the total current I from which each point of the IV curve can unambiguously be specified. The normal case is described by an increase of local voltage V_{ij} and currents I_{ij} with the total current I. At low current densities, substantial self-heating does not occur, and all curves for different positions on the substrate coincide as indicated in Fig. 5 a). This also implies that the sheet resistance of the transparent electrode does not noticeably affect the current flow. However, upon

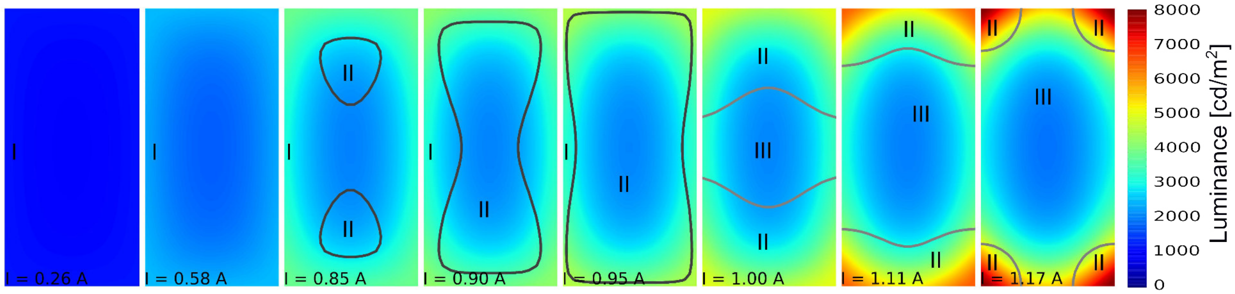


Figure 4. Luminance distribution as revealed by an electrothermal simulation using a multi-physics network model. Parameters like the size, the activation energy $E_{\mathrm{a}} = 200\,\mathrm{meV}$, and the sheet resistance $R_{\mathrm{sh}} = 8\,\Omega$ are chosen to match the experimental characteristics obtained from Fig. 2. The relation between current density and voltage is fitted by a power-law from an isothermal operation regime. Luminance values have been derived from the calculated current density incorporating the effect of roll-off. Reproduced with permission.[6] Copyright (c) 2014 Wiley-VCH.

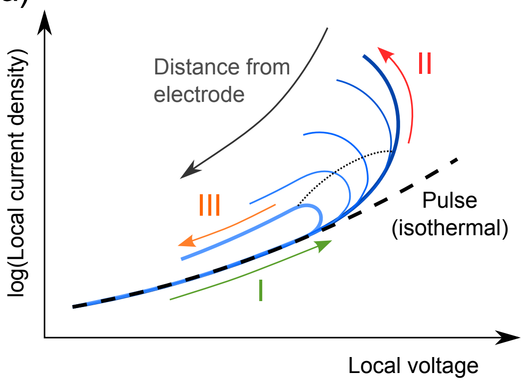
elevated self-heating, the situation changes. One can show that the current-voltage characteristic of an OLED tends to show S-shaped negative differential resistance (S-NDR) which strongly depends on the position on the lighting panel.[6] Regions farthest away from the edges first enter an operation mode at which the local voltage drop decreases although the current density is still increasing, as shown in Fig. 4 at a current of $I = 0.85\,\mathrm{A}$. Two areas operating in regime II arise at inner positions of the lighting panel, and expand until they merge at higher currents.

This raises the question why these local NDR regions first occur at central positions but not at the edges where the highest power dissipation and temperatures are observed. One has to consider the interaction between all of the thermistor devices in the array. They are not only coupled electrically by the sheet resistance of the electrodes but also thermally by the glass substrate. Thus, neighboring thermistors are able to exchange heat, so that the local differential resistance is not anymore a unique property of each thermistor cell, but rather characterizes the behavior of a thermistor in an environment of surrounding thermistor devices. For example, it is possible that the increase of the current density in inner parts of a lighting panel does not result from an increase in local voltage, but it is induced by the heating from the environment which raises the conductivity and enhances the current flow even though the local voltage has not been changed significantly. A local NDR can then also arise when local voltages decrease and local currents still increase due a strong enhancement of the conductivity by a global heating of the panel*.

Areas where the local voltages decrease under growing external current and voltage are marked as regime II in Fig. 5 b). They introduce a further new phenomena to large area OLEDs upon self-heating.[6] As predicted by simulations, the occurrence of NDR introduces a situation where local voltages even close to the edges are decreasing, and the lateral heat conduction by the substrate is not sufficiently high to warm up central regions of the panel. Then, it is possible that both local voltages and local currents decrease as only a part of the externally applied voltage reaches the central position of the device. The local voltage just falls back by the fact that areas being in regime III 'see' a decreasing local voltage passed through by areas with local NDR lying between them and the outer contacts. For that reason, we call them 'switched-back'-regions. Up to now, this effect has not been proven experimentally, but the fact that the luminance of the OLED lighting panel investigated saturates in the center already indicates the onset of a decrease of the local currents there. The presence of these switched-back regions also explains why local NDR is observed first most far away from the edges. In order to have a transition from regime I (normal) to regime III (switched-back), it is inevitable for a certain area of the device to pass trough regime II (NDR). This can be seen in Fig. 5 a) where IV curves of different positions on the panel are presented schematically.

*A guiding example considering a chain of coupled thermistor devices can be found in Ref. 16, illustrating the occurence of different operation modes.

a)



b)

current \ voltage	$\frac{dV_{\mathrm{ij}}}{dI} > 0$	$\frac{dV_{\mathrm{ij}}}{dI} < 0$
$\frac{dI_{\mathrm{ij}}}{dI} > 0$	$\frac{dV_{\mathrm{ij}}}{dI_{\mathrm{ij}}} > 0$ normal (I)	$\frac{dV_{\mathrm{ij}}}{dI_{\mathrm{ij}}} < 0$ S-NDR (II)
$\frac{dI_{\mathrm{ij}}}{dI} < 0$	$\frac{dV_{\mathrm{ij}}}{dI_{\mathrm{ij}}} < 0$ N-NDR (not present)	$\frac{dV_{\mathrm{ij}}}{dI_{\mathrm{ij}}} > 0$ switched-back (III)

Figure 5. a) Local IV curves for different positions on the lighting panel. Upon self-heating, each part of the device behaves differently, depending on the local temperature, power dissipation and thermal environment. For comparison, an isothermal curve is shown, e.g. measured by short pulses, valid for all positions within the device area. The dotted line connects points of each IV curve corresponding to the same total current I, illustrating that regions most far away from edges enter regime II and III first. b) Table with possible scenarios of local device operation. In regime I, the device behaves normally: Local voltages and current densities increase with the total current I. When local parts of the lighting panel enter regime II, local NDR occurs, so that the local voltage drop decreases although the local current density still increases. In a third regime of operation, it is even possible that the OLED behaves like 'switched-back'. In these regimes, both voltage and current density locally decrease while the externally measurable current still increases.

2.3 Conclusion

In this article, we have described the consequences of electrothermal feedback in OLEDs with emphasis on large area lighting panels. In particular, the saturation of luminance at the center of the devices can only be explained by considering a strong feedback between the temperature-activated conductivity and the dissipation power. As a result, negative differential resistance can be observed in OLEDs, adversely affecting the brightness homogeneity. Simulations even reveal the possible presence of switched-back regions where the local current and local voltage decrease although the external current still increases.

Future work on that topic will concentrate on a more detailed comparison between experiment and simulation. Especially, the description of the conductivity-temperature relation has to be determined in detail by 4-wire crossbar measurements excluding the external series resistance which typically hampers the determination of the correct device behavior at high currents and temperatures. A detailed analysis of the problem also requires a simulation tool accounting for arbitrary shapes of the devices and heat convection, which is why approaches solving partial differential equations are superior to multi-physics network models, even though latter can give quick and valuable insights to the problem.[16] However, a correct reproduction of the nonlinear effects, e.g. the switching phenomena induced by NDR, is necessary in order to predict device operation correctly for different size and shape at the highest current. If this will be possible, new optimization strategies can be evaluated on a larger range of parameter variations. We believe that not only higher luminance in combination with a good homogeneity can be achieved, but also the operational stability can greatly benefit from such optimizations based on an excellent understanding of non-linear electrothermal feedback in OLEDs.

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